Understanding eA at eRHIC: A BeAGLE Update

Mark D. Baker

11-MAY-2017

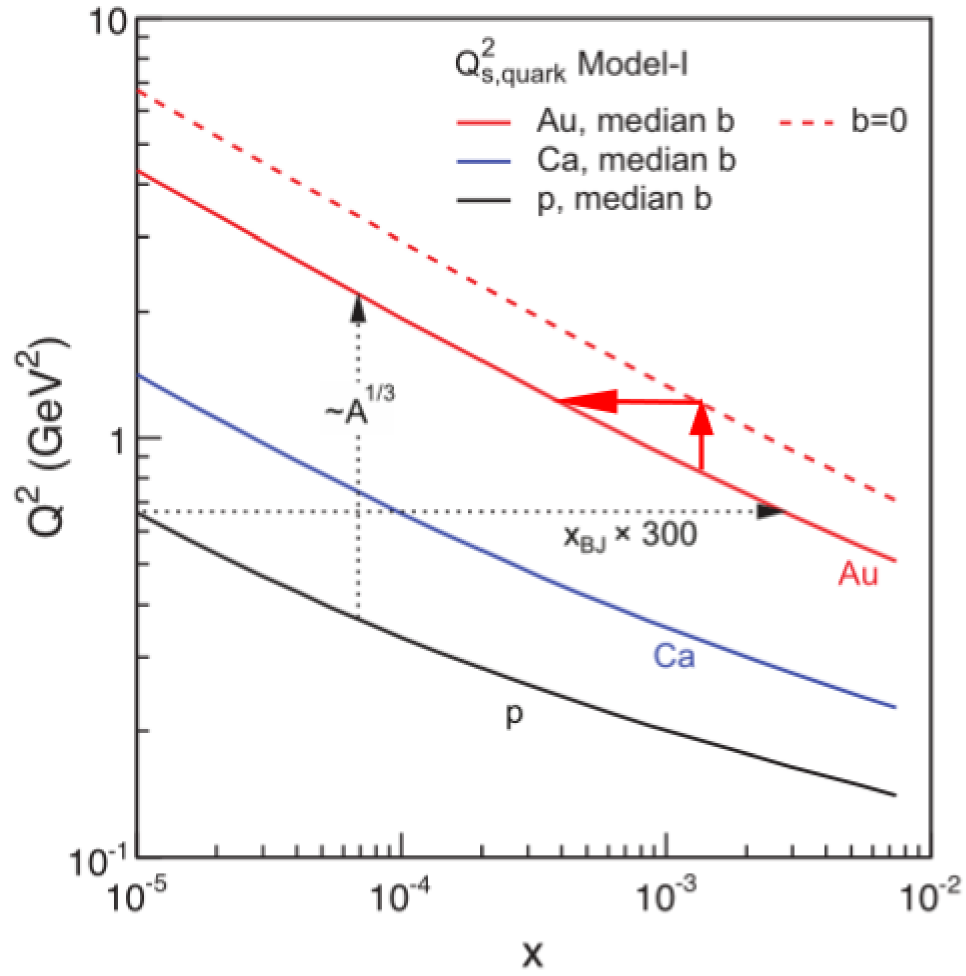
BeAGLE/eRD17 collaborators: Elke, JH & Liang

Advice/Help from: Raju, Thomas, Alexander &...

JLAB LDRD crew: C. Hyde, T. Toll, P. Turonski,
V. Morozov, G. Wei, R. Dupré, A. Accardi...

Main physics question for today

Can we enhance Q_s using geometry tagging?



Adapted from
EIC White Paper

"Geometric oomph" ~ Thickness

$Q_s^2 \sim A^{1/3}/x^{\lambda}$ $\lambda \sim 0.3$

$A_{eff}^{1/3} \sim T(b)$

Oomph = $\langle T(b)\rangle_{central} / \langle T(b)\rangle_{minbias}$

$T(b) \equiv \int_{-\infty}^{\infty} \rho(z,b)\, dz$ in nucleons/fm^2

$T_{scl}(b) \equiv \int_{-\infty}^{\infty} \rho(z,b)/\rho_0\, dz$ in units of fm

Benchmark eA Generator for LEptoproduction (BeAGLE)

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+------------------------------------------------------------------------+
| Welcome to BeAGLE - Benchmark eA Generator for LEptoproduction         |
|                                                                        |
|         BBBBBB  EEEEEEE     A     GGGGGG  LL       EEEEEEE             |
|         BB   B  EE         A A    GG      LL       EE                  |
|         BB  B   EE        A   A   GG      LL       EE                  |
|         BBBBB   EEEEE     AAAAA   GG  GG  LL       EEEEE               |
|         BB  B   EE       A     A  GG   G  LL       EE                  |
|         BB   B  EE       A     A  GG   G  LL       EE                  |
|         BBBBBB  EEEEEEE  A     A  GGGGGG  LLLLLLL  EEEEEEE             |
|                                                                        |
| Pre-release version                                                    |
|                                                                        |
| Authors: Elke Aschenauer, Mark D. Baker, J.H. Lee, Liang Zheng         |
| Contact: liangzhphy@gmail.com or mdbaker@mdbpads.com                   |
|                                                                        |
| This program (previously called DPMJetHybrid) links to:               |
| DPMJET, PHOJET, & PYTHIA (see version #s below) including also         |
| LHAPDF for pdfs, and FLUKA & PyQM for conventional nuclear effects     |
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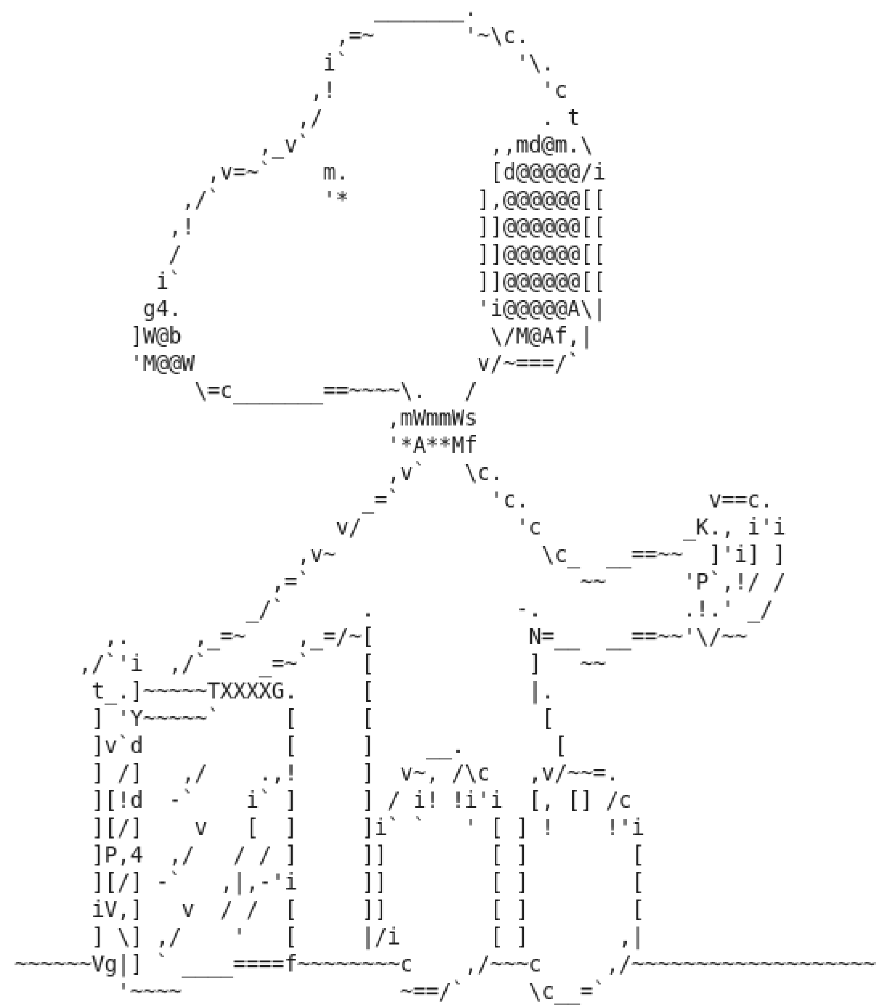
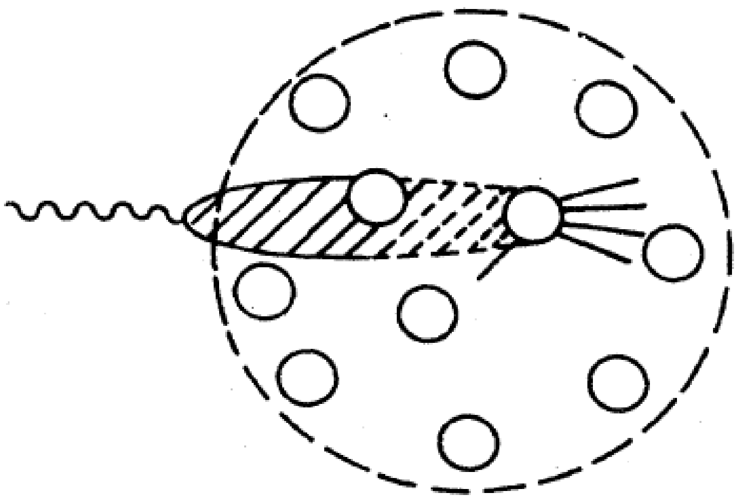


Art credit: asciiworld.com

- DPMJET-> DPMJETHybrid -> BeAGLE
- DIS hard process
- Initial and final cold nuclear effects
- Reasonable estimation of the nuclear remnant breakup
- Now installed at JLab and BNL both
- Works with GEMC and eic-smear (*)

What's new about BeAGLE? Multinucleon shadowing


(c)

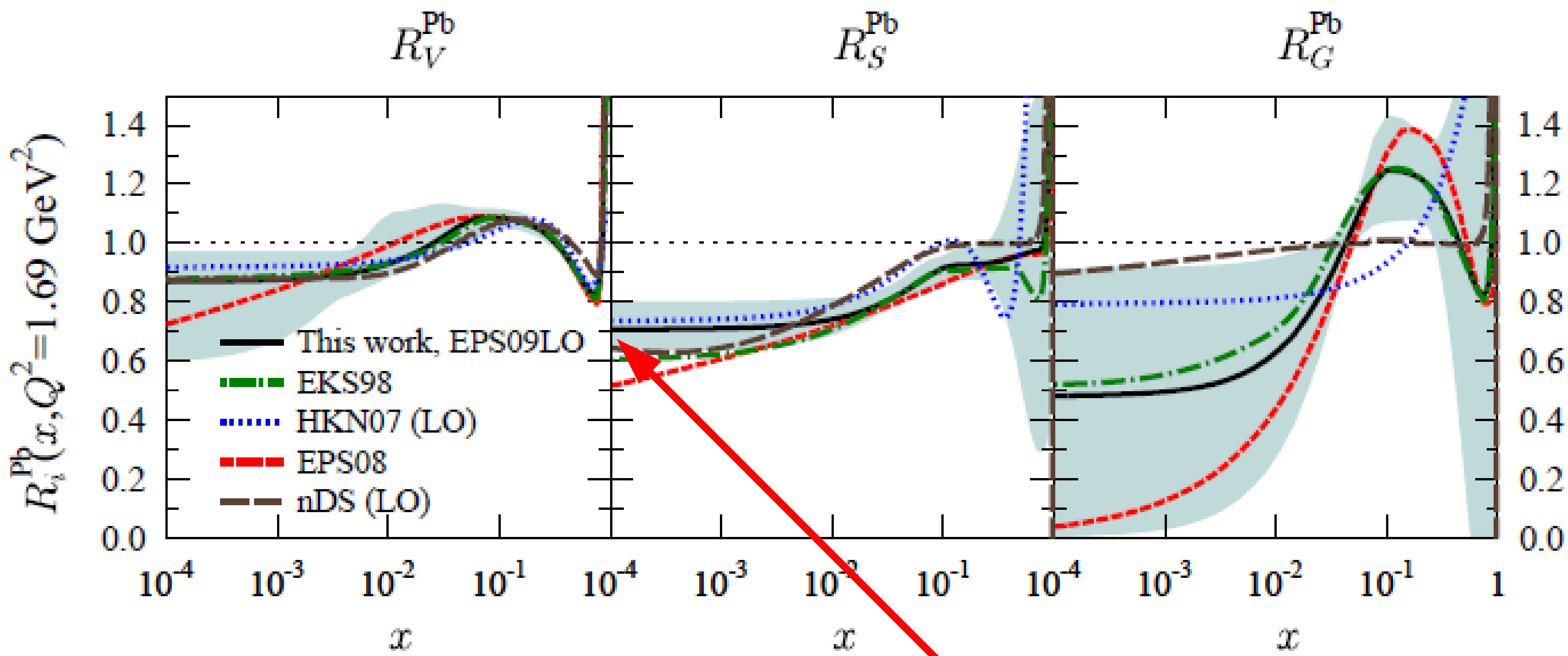
Targ. RF picture of the γ^*:

- Sometimes point-like with σ~0
- Sometimes hadronic ("dipole") σ~few mb
- Time fraction such that total σ_{ep} correct
- Coherence length of "dipole" is λ~1/(2Mx)

Do NOT model shadowing / saturation in detail to find $\sigma_{dipole}(x,Q^2)$!

Rather, use an input value of nuclear shadowing $R^{Au}(x,Q^2)$ to find $\sigma_{dipole}(x,Q^2)$. Then model probability of multiple nucleon DIS.

Simplified R using $F_2^{EPS09LO}(x,Q^2)$



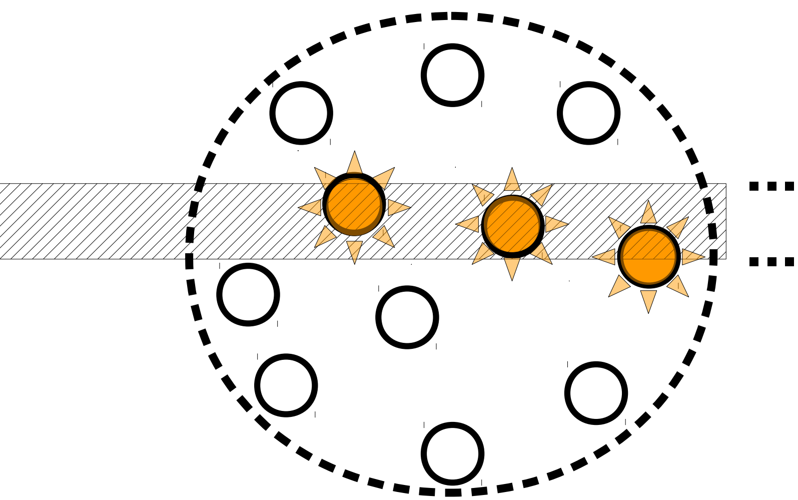
$R(x \to 0, Q^2=1.69GeV^2) \equiv y_0(A) = 0.890\ (A/12)^{-0.0803} = 0.711$ for Au

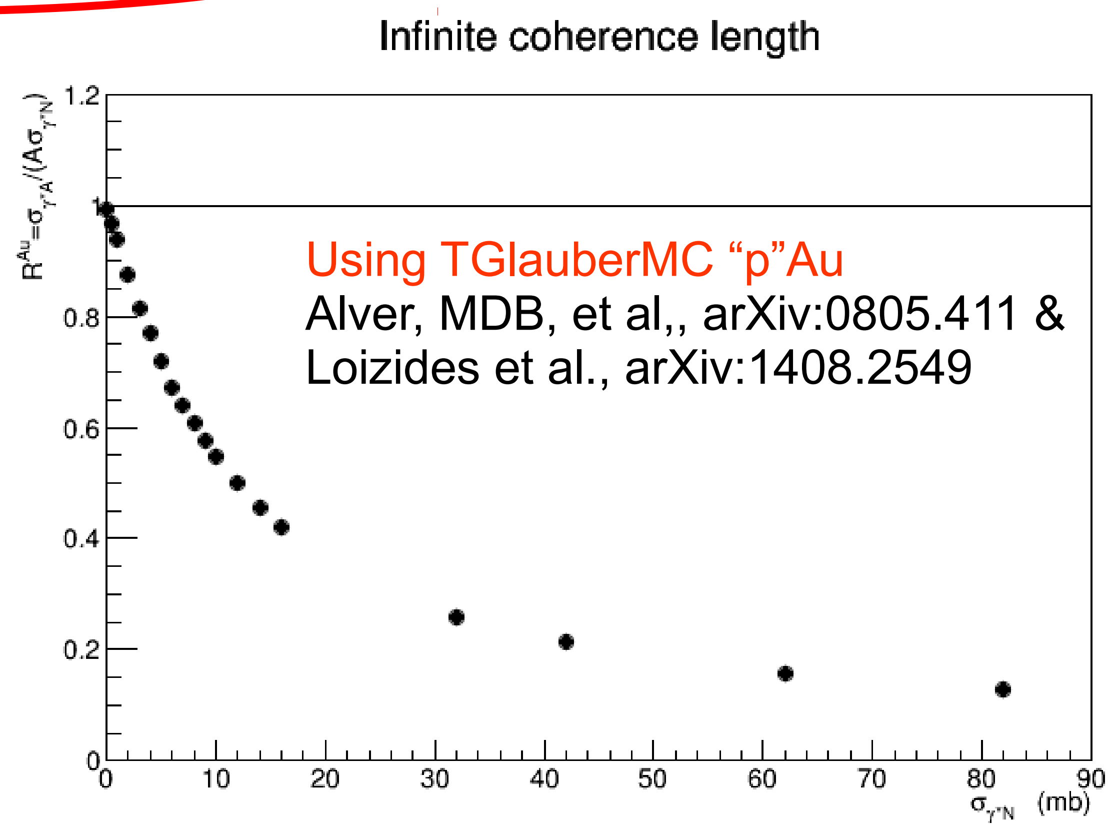
0.708 for Pb

Making the map for λ>>R

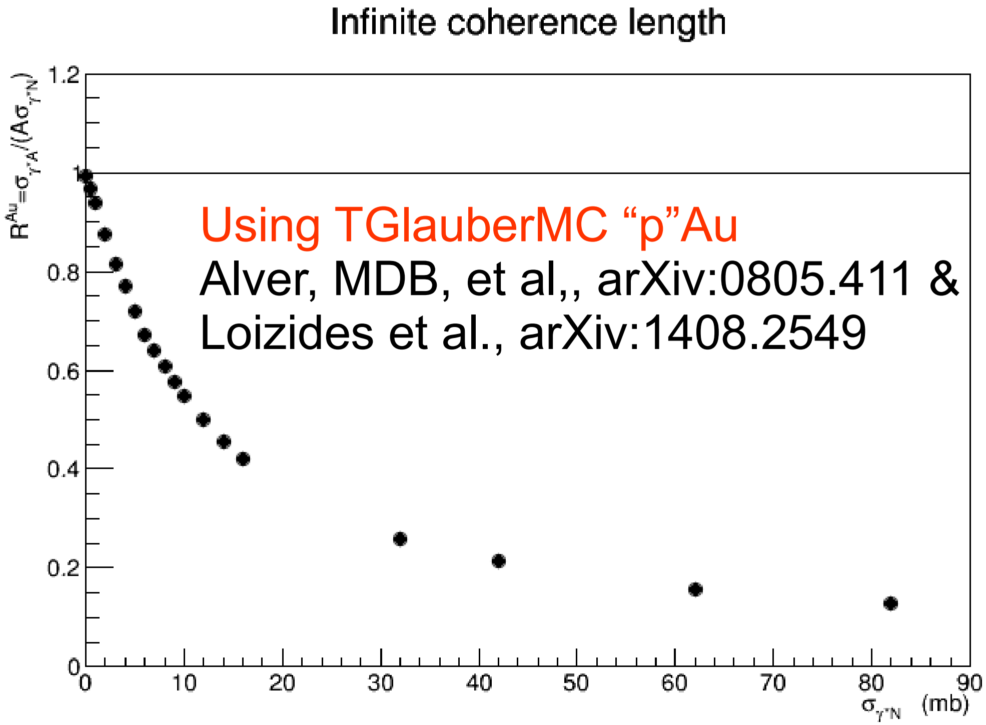
Most of the complications in saturation theory are in predicting the dependence on x, Q^2. With Glauber, we can make a simple map:

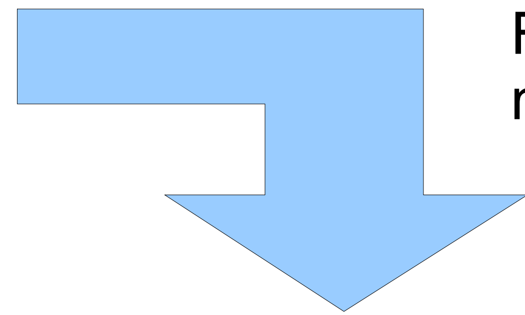
$\sigma^A/\sigma^N(x,Q^2)$ ⟷ $\sigma_{\text{“dipole”}}(x,Q^2)$ ⟷ $P(N_{coll},b)$



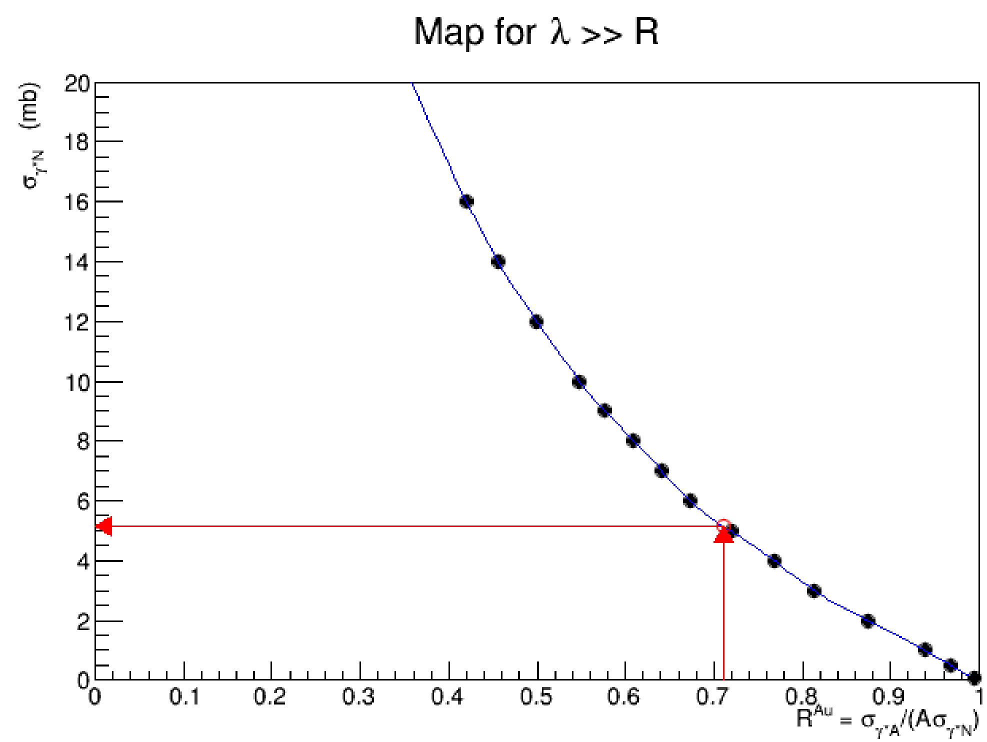


Looking up the appropriate $\sigma_{\gamma^*N}(x,Q^2)$





Flip axes to make map.



Event-by-event, given x & Q^2:

E.g. for x=0.001, Q^2=1.69 GeV^2

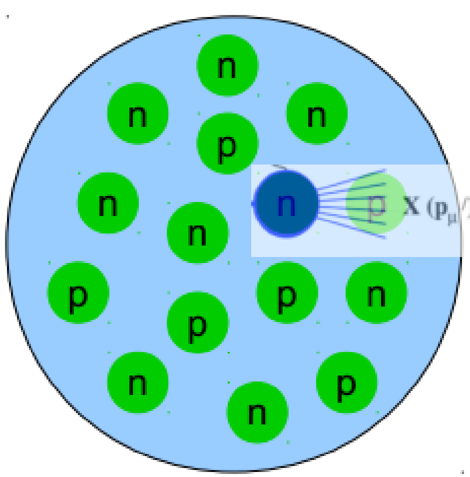
$R^{(Au/N)}(x\to 0, Q^2=1.69 GeV^2) \approx 0.711$

$\sigma_{\text{"dipole"}}$ = 5.16 mb

Nuclear Shadowing in BeAGLE

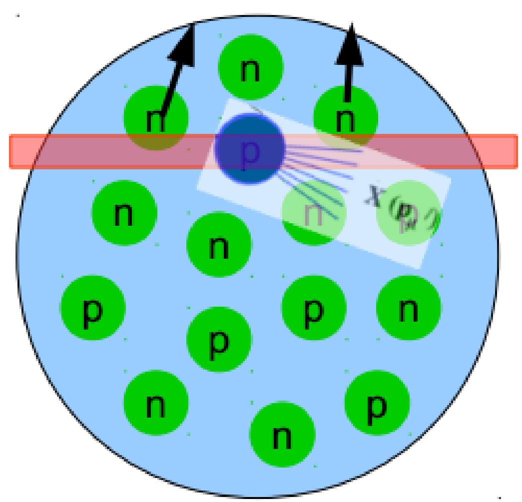
No dynamic shadowing: genShd=1

Pick one nucleon randomly from the Glauber configuration and replace it by PYTHIA results



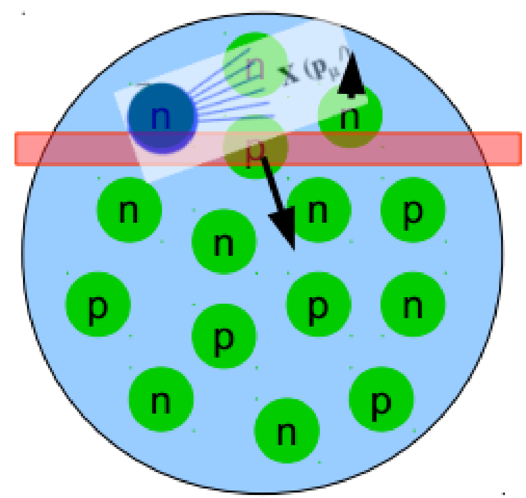
With dynamic shadowing: genShd=2

Multiple nucleons involved, pick one to do hard scattering in PYTHIA, others elastic



With dynamic shadowing: genShd=3

Multiple nucleons involved, pick the first one on the way to do hard scattering in PYTHIA, others elastic

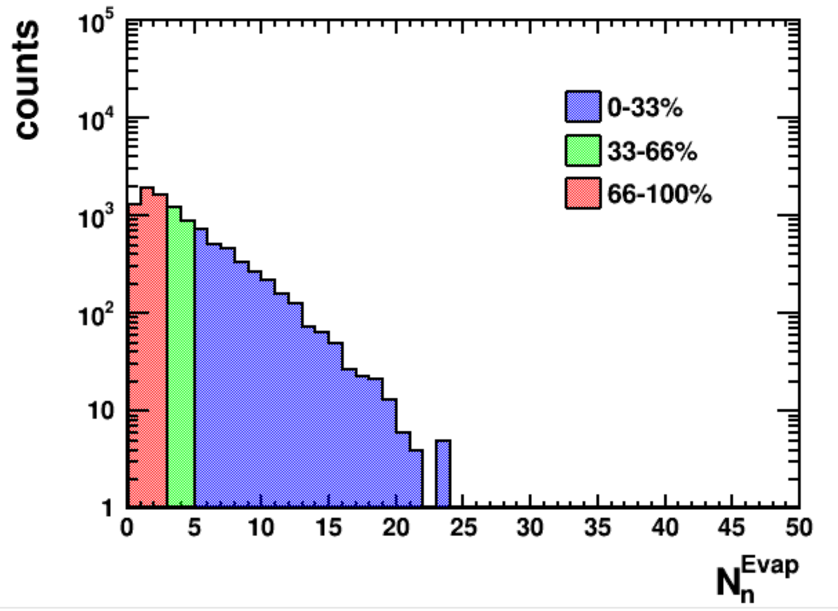


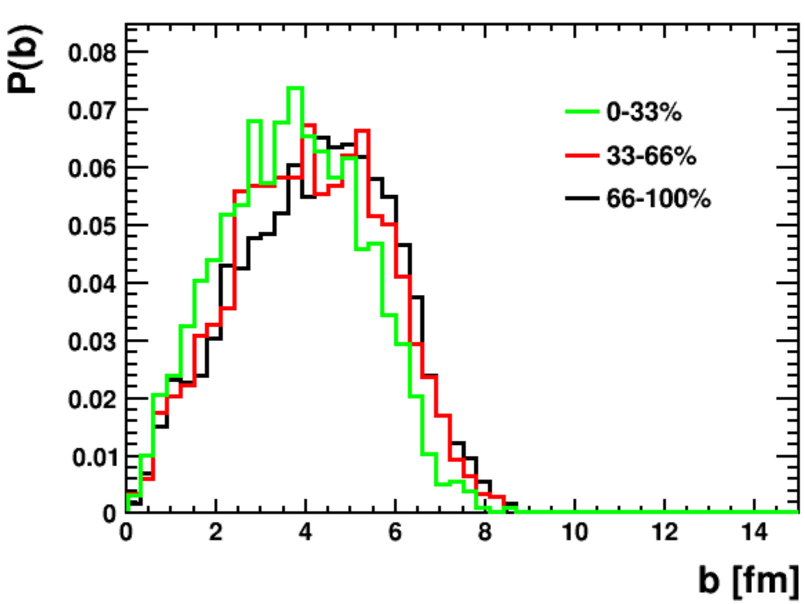
Measuring b with a ZDC: Try 1

From Slide 25 of Liang's 4/13 TF talk:

eAu 10x100 GeV, $1<Q^2<20$ GeV^2, $0.01<y<0.95$, 33% centrality cuts

GenShd=1 (no multi-nucleon shadowing – like DPMJetHybrid)





A bit disappointing...

Measuring b with a ZDC: Try 1

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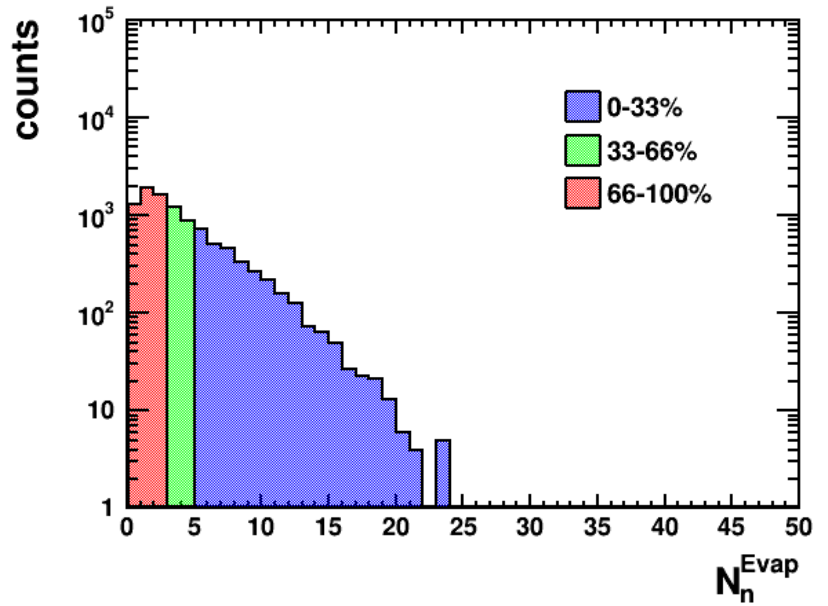
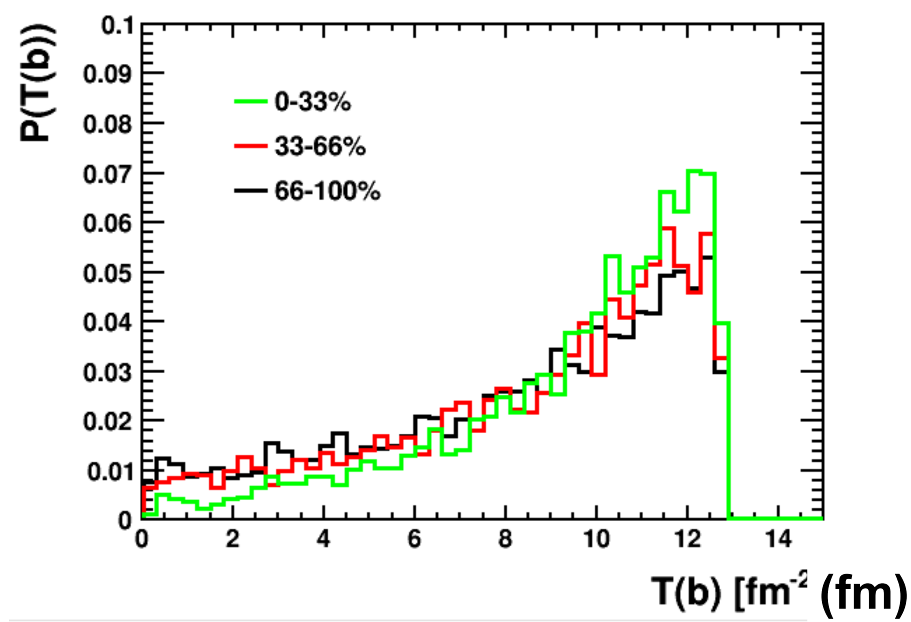




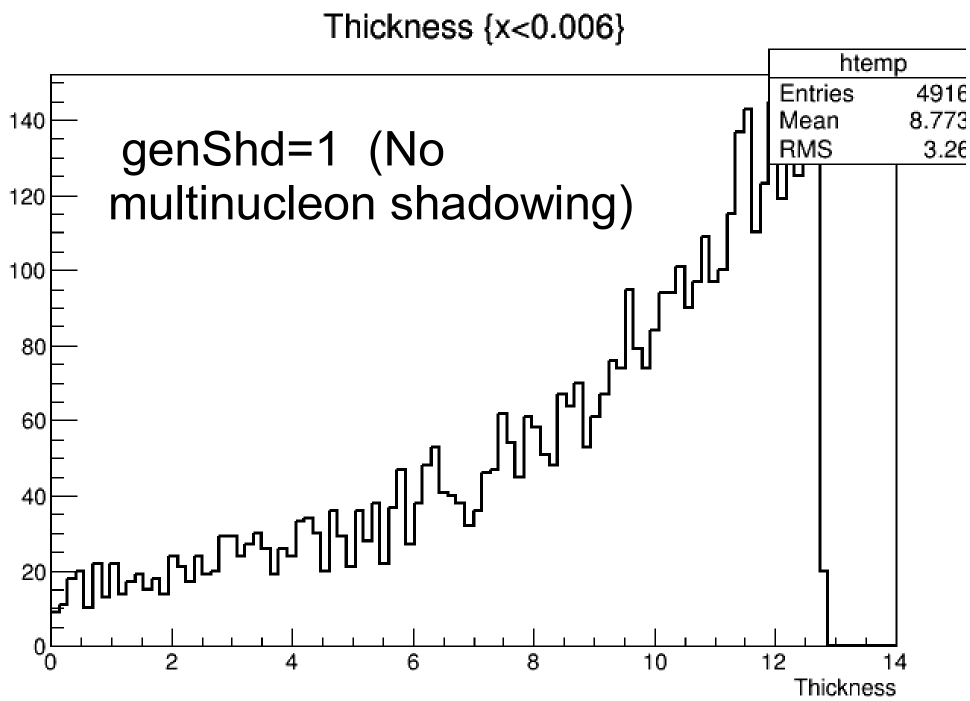
Not a lot of oomph here...

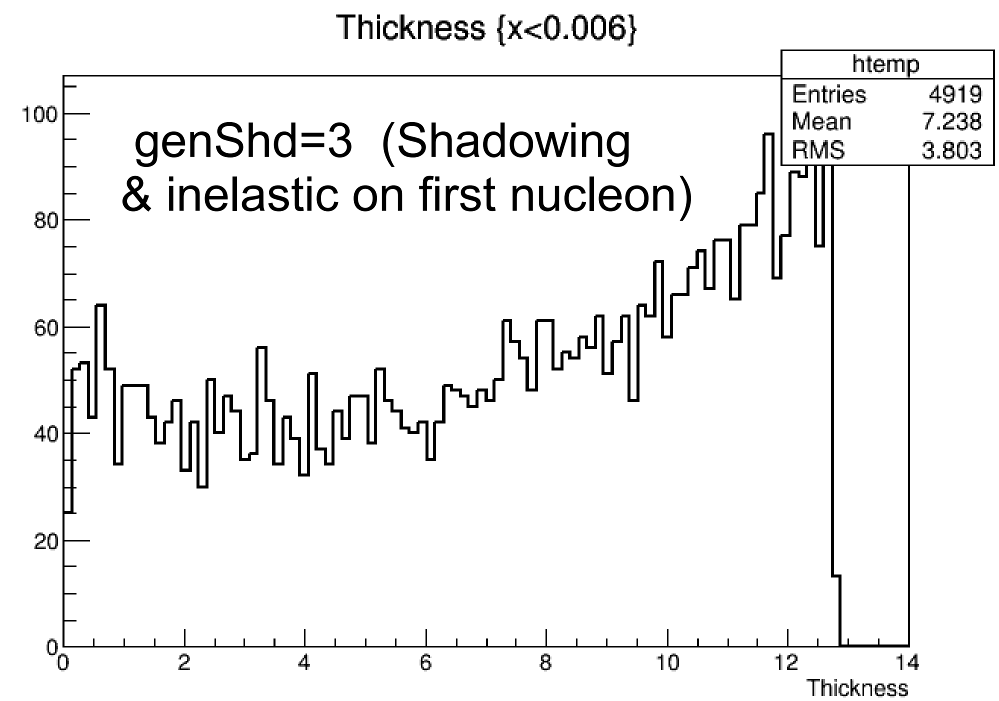
Let's Try Harder!

- Tighter cuts. 33% is pretty loose.
- Use multinucleon shadowing (genShd=3)
- Use $x<0.006$ (about half the data sample)

Minbias T(b) depends on genShd

eAu 10x100 $x<0.006$, $Q^2>1$ GeV^2

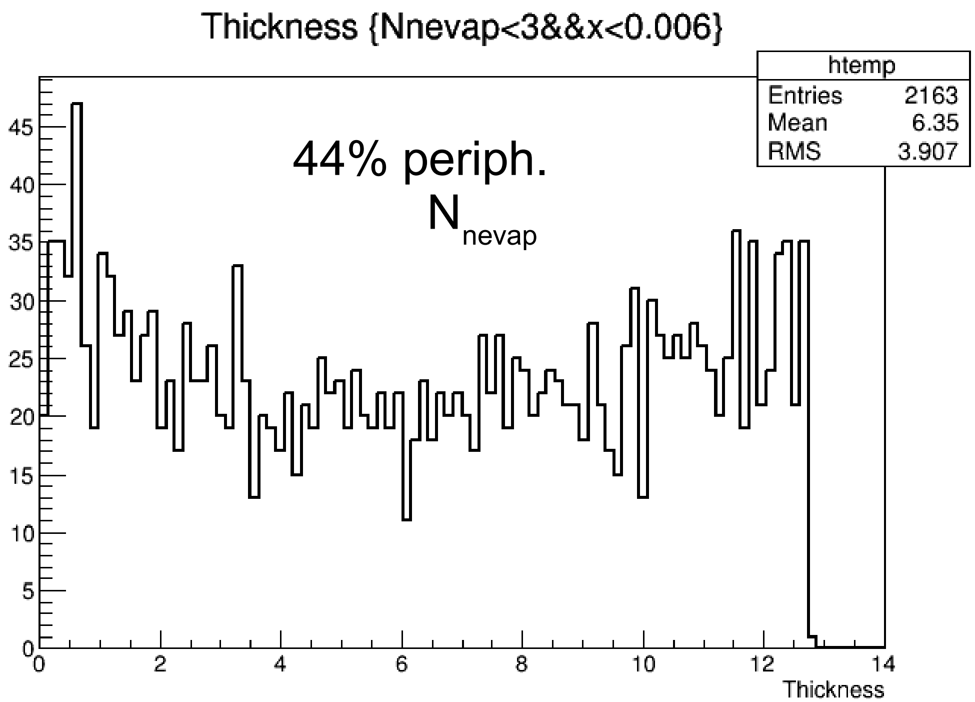


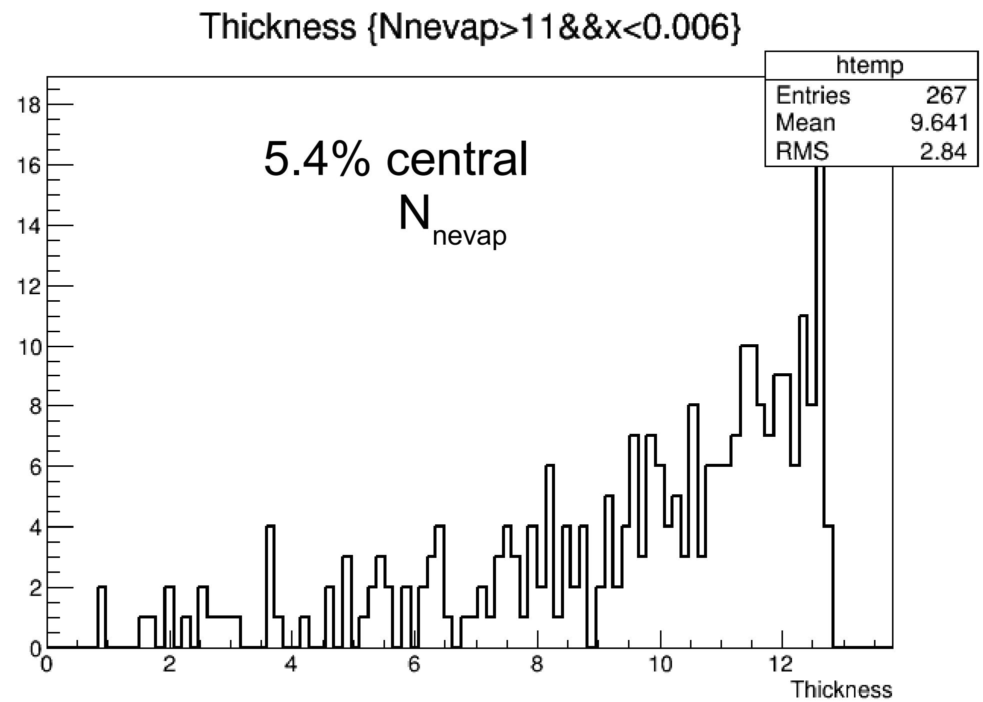


Shadowing suppresses b=0 vs. b~R
So it suppresses large T values.

Tight cuts DO work for T(b)!

eAu 10x100   x<0.006, Q^2>1. genShd=3 (Shadowing & inelastic on first nucleon)

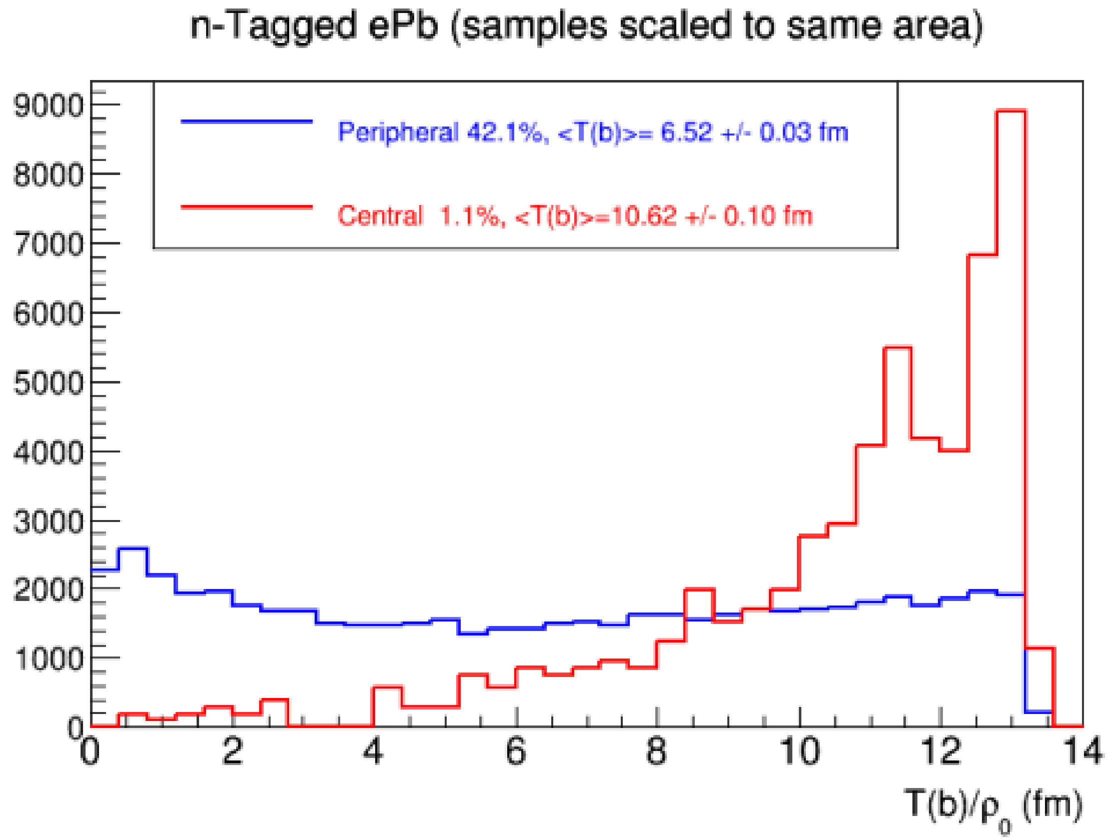




$\langle T \rangle_{cent} / \langle T \rangle_{minbias}$ = 9.641fm / 7.238fm = 1.332 for 5.4% central cut

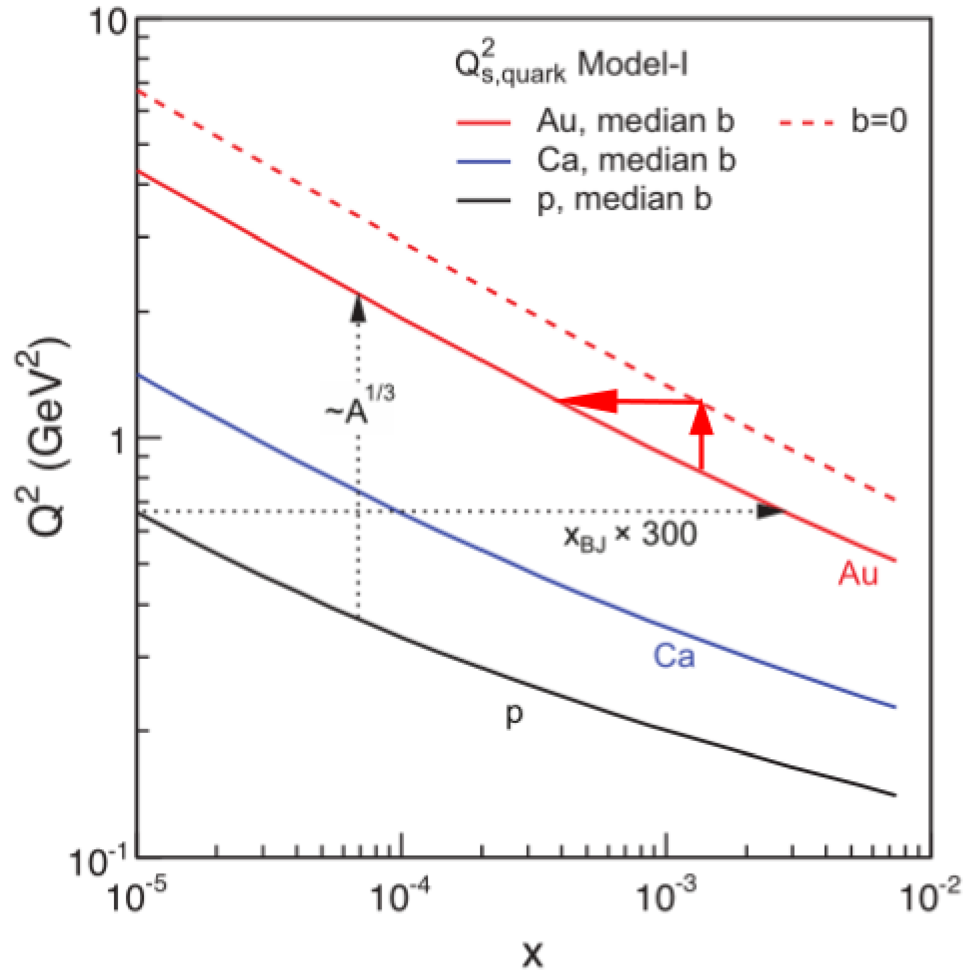
Higher stats. ePb 10x40, x<0.002

ePb 10x40 x<0.002, Q^2>1. genShd=3 (Shadowing & inelastic on first nucleon)



$\langle T\rangle_{cent}/\langle T\rangle_{minbias}$ = 10.62fm / 7.50 fm = 1.42 for 1.1% central cut

Effective x (or E_{beam}) boost?



Adapted from
EIC White Paper

Energy Impact Factor?

$Q_s^2 \sim A^{1/3}/x^{\lambda}$ $\lambda \sim 0.3$

$A_{eff}^{1/3} \sim T(b)$ $x \sim Q^2/(ys)$ $s/A \sim 4E_eE_A/A$

Energy Impact Factor?

$Q_s^2 \sim A^{1/3}/x^{\lambda}$ $\lambda \sim 0.3$

$A_{eff}^{1/3} \sim T(b)$ $x \sim Q^2/(ys)$ $s/A \sim 4E_eE_A/A$

$Q_s^2 \sim T(b) * (E_eE_A)^{0.3}$

Energy Impact Factor?

$Q_s^2 \sim A^{1/3}/x^\lambda$ $\lambda \sim 0.3$

$A_{eff}^{1/3} \sim T(b)$ $x \sim Q^2/(ys)$ $s/A \sim 4E_eE_A/A$

$Q_s^2 \sim T(b)*(E_eE_A)^{0.3}$

$\langle T(b) \rangle_{cent}/\rho_0 = 10.62$ fm $\langle T(b) \rangle_{minbias}/\rho_0 = 7.50$ fm

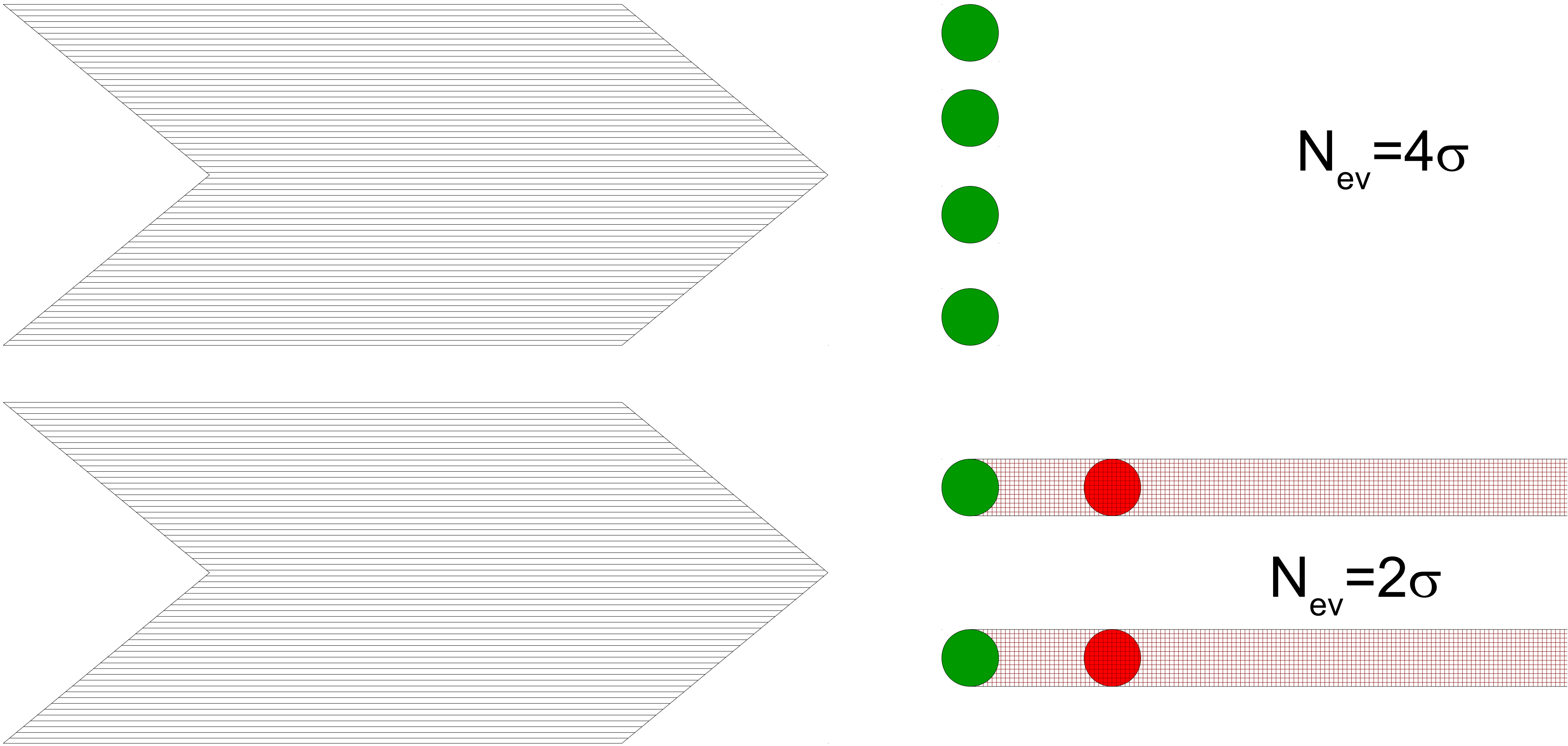
$$E_{enhancement} \sim [T(b)_{cent}/T(b)_{minb}]^{10/3}$$
$$\sim [10.62 / 7.50]^{10/3}$$
$$\sim \textbf{3.19!}$$

Conclusion

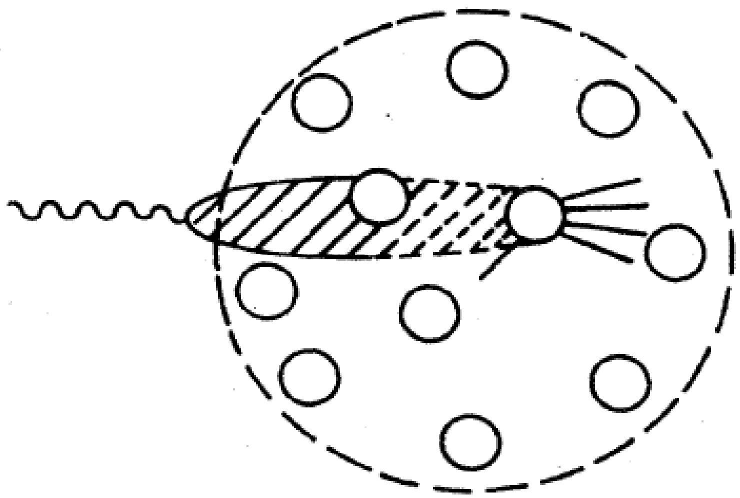
- BeAGLE is on mass-shell now
- Encouraging results for centrality tagging for saturation enhancement:
  - $O(10^{1/2})$ enhancement in effective x (or E_{beam})
  - Or effective A like 600 ($A_{eff}=A^{*}\langle T\rangle^{3}_{cent}/\langle T\rangle^{3}_{mb}$)

Extras

Simple Classical Shadowing



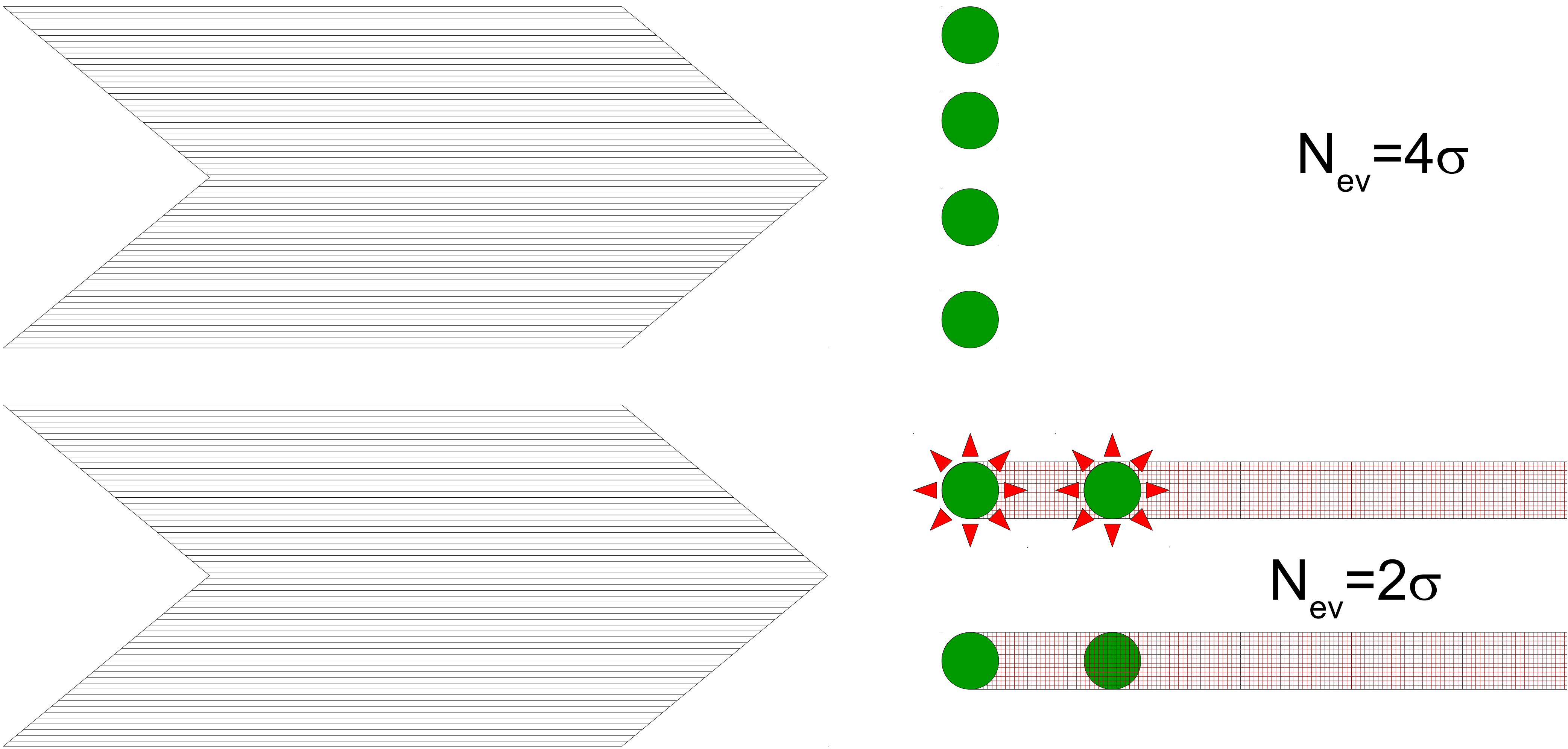
Quantum collisions still shadow



The virtual photon spends part of it's time as a hadronic state (“dipole”) with a coherence length of λ~1/(2Mx).

So at low x it can hit BOTH the front and the back (“shadowed”) nucleon. But the number of events is still reduced compared to the case of A nucleons “side-by-side”!

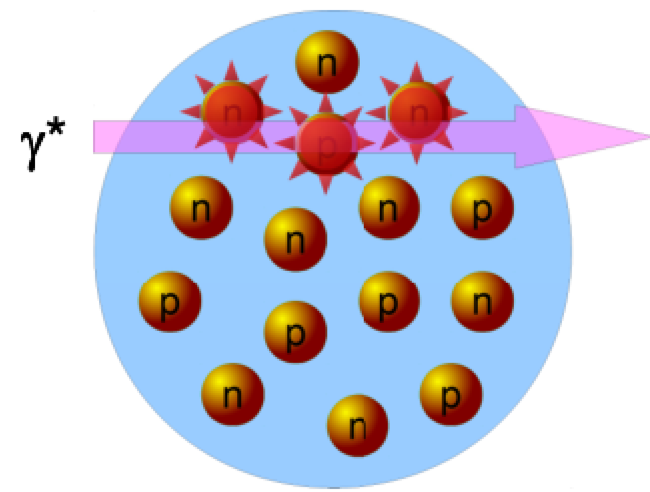
Quantum Shadowing (large λ)



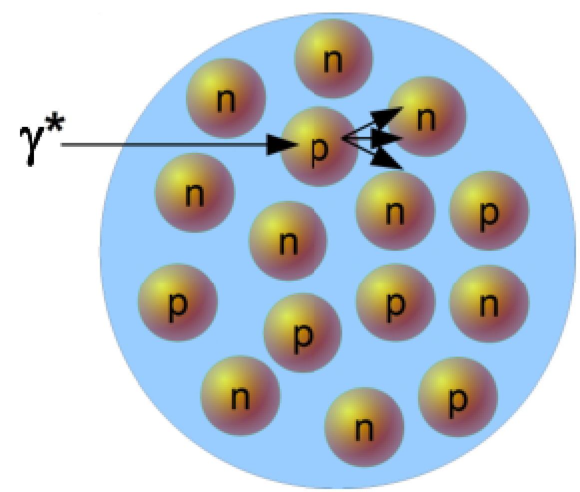
What is "Shadowing"

Shadowing can be defined as:

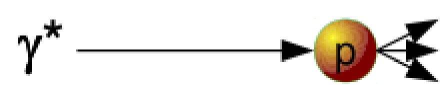
$\sigma(eA) < A\,\sigma(ep)$



It can, in principle be caused by literal shadowing, where the effect is dynamical and involves multiple nucleons...



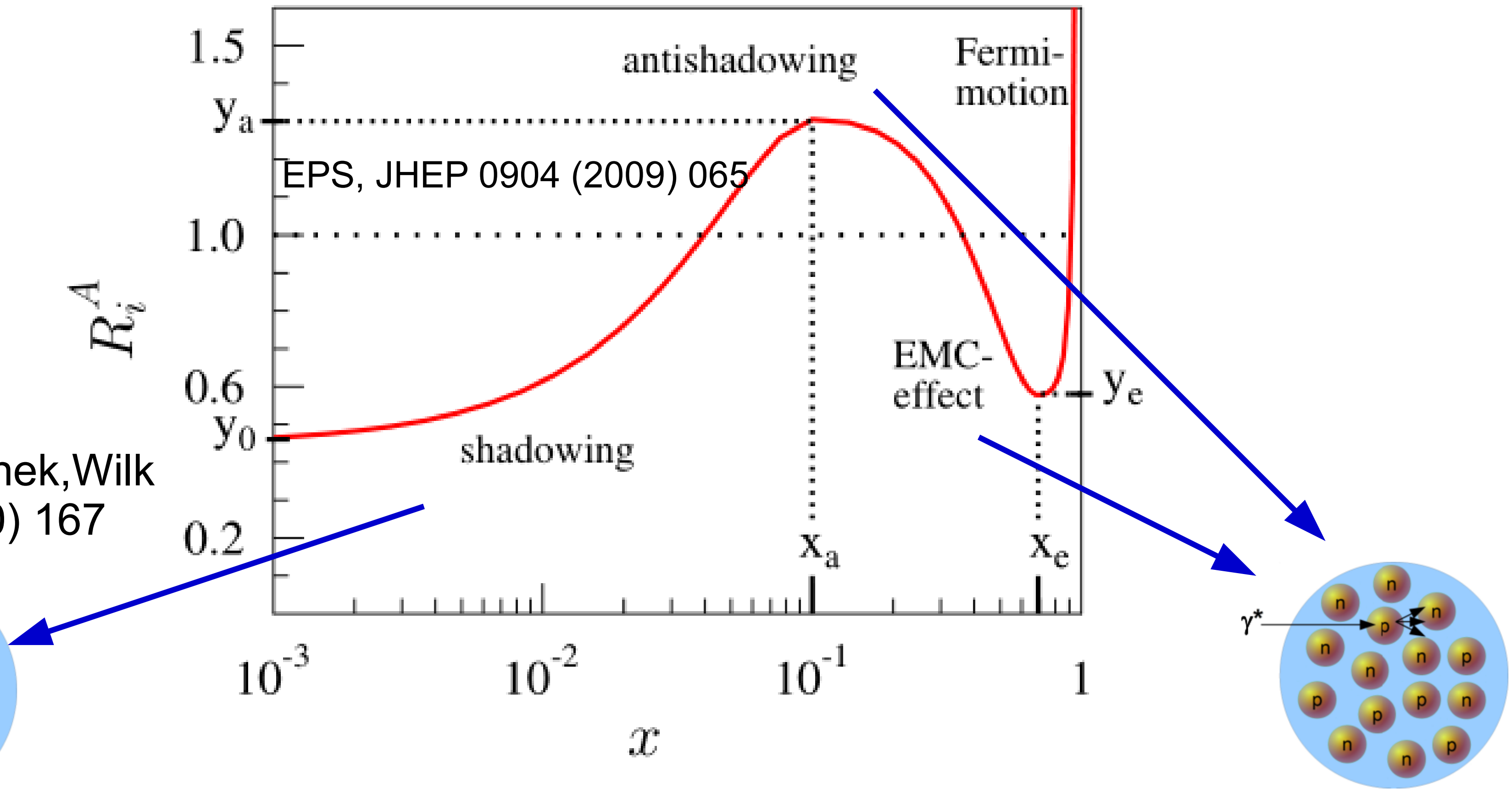
Or by modification of the individual nucleons on a slow timescale, followed by point-like interaction of the probe.



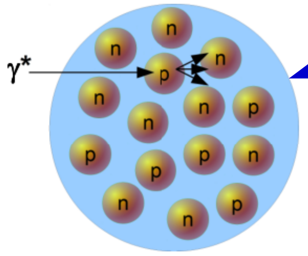
Or both??

DPMJetHybrid approach = BeAGLE: genShd=1

Alternate approach: Nucleons (or their pion cloud) change, but not the photon or the interaction. Can we rule this out for low x eA?



See e.g. Rożynek,Wilk PLB 473 (2000) 167

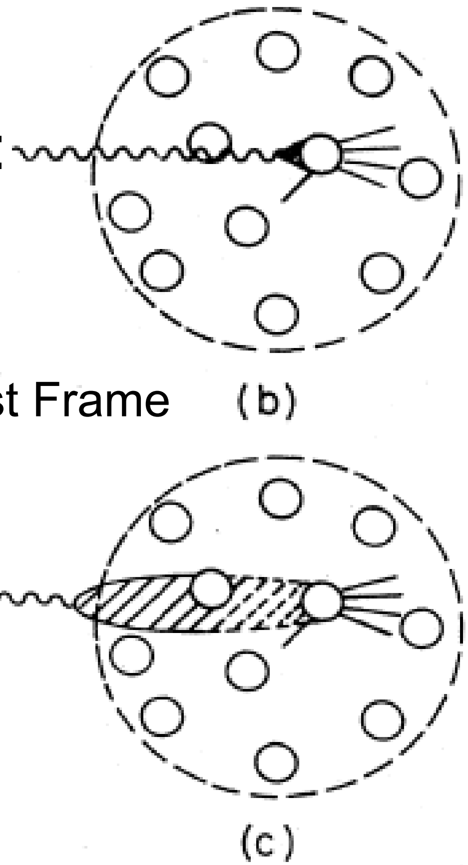


eA: Basic Quantum Mechanics

$\hbar = c = 1$ $r = 0.88$ fm $1/(2Mr) = 0.12$ $\Delta p_z \Delta z = 1/2$

Bauer, Spital, Yennie, Pipkin
Rev. Mod. Phys. 50 (1978) 261

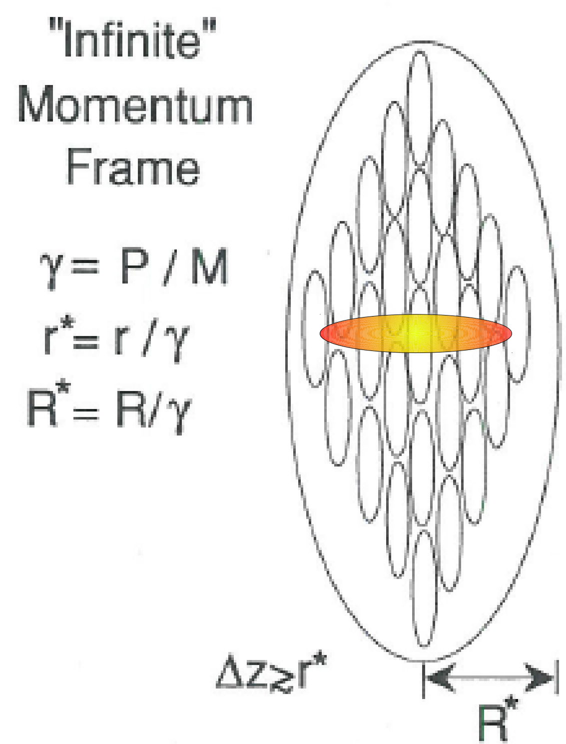
High x_{Bj}:



Nucleus Rest Frame

Low x_{Bj}:

$\lambda_h / r \approx 1/(2Mxr) = 0.12/x_{Bj}$



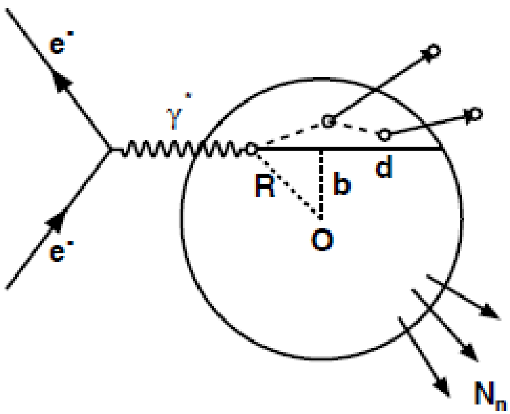
$p_z^{quark} = Mx\gamma$

$\Delta z = 1/(2Mx\gamma)$

$\Delta z / r^* = 1/(2Mxr)$
$= 0.12/x_{Bj}$

For $x_{Bj} << 0.12$, parton wavefunctions and/or interaction cannot be localized.

Geometry tagging b vs. d

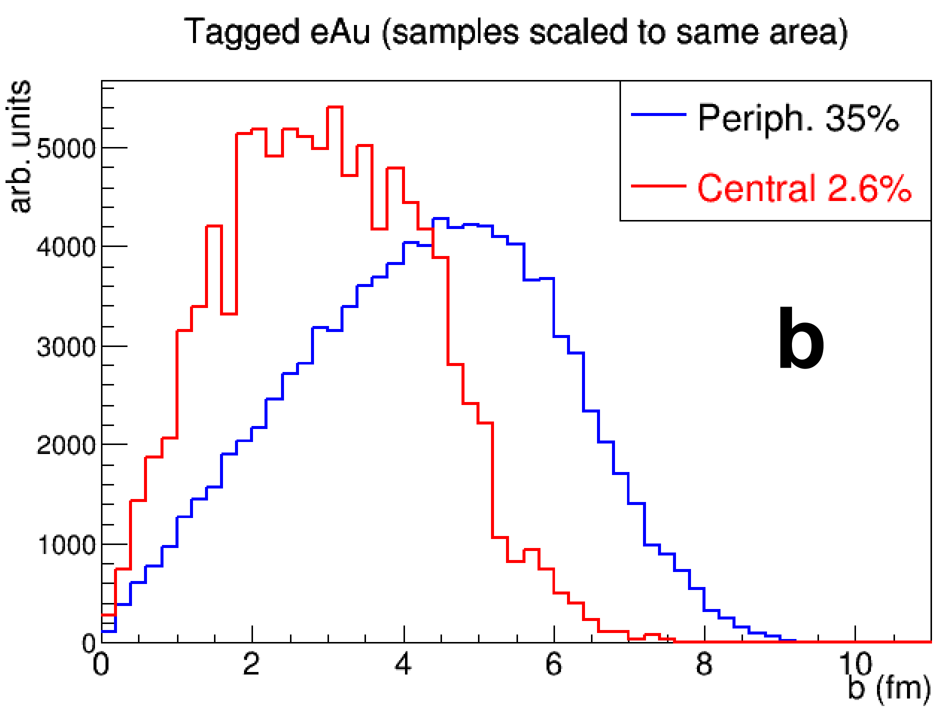


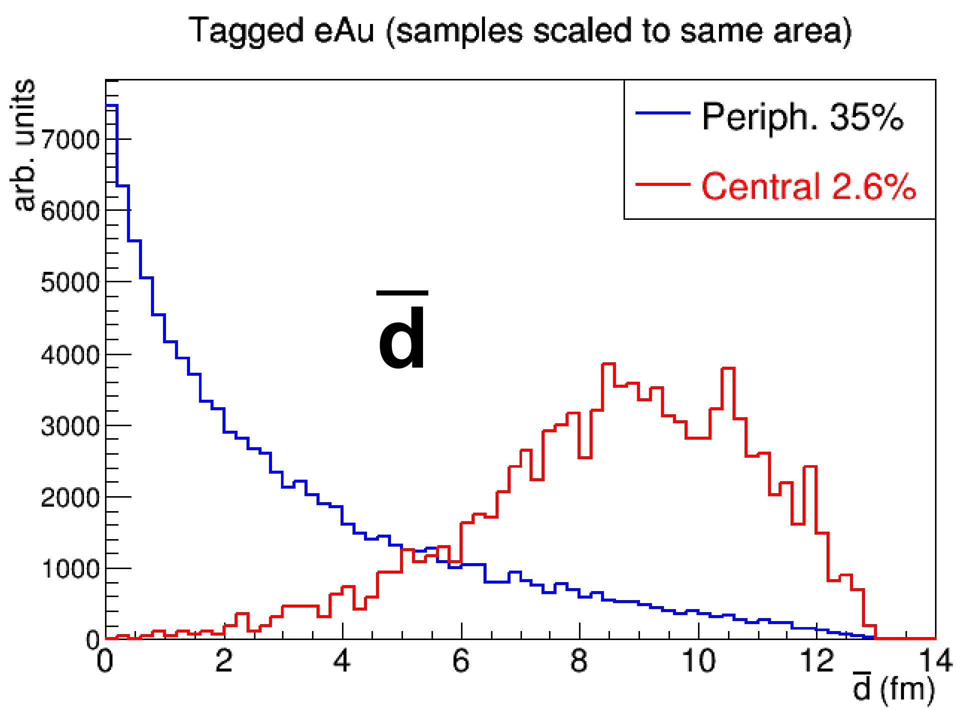
Intra-nuclear cascading increases with d (forward particle production)

Leads to more evaporation of nucleons from excited nucleus (very forward)

Evap. n - tagged eAu
No shadowing

b is indirectly taggable because it correlates with d.

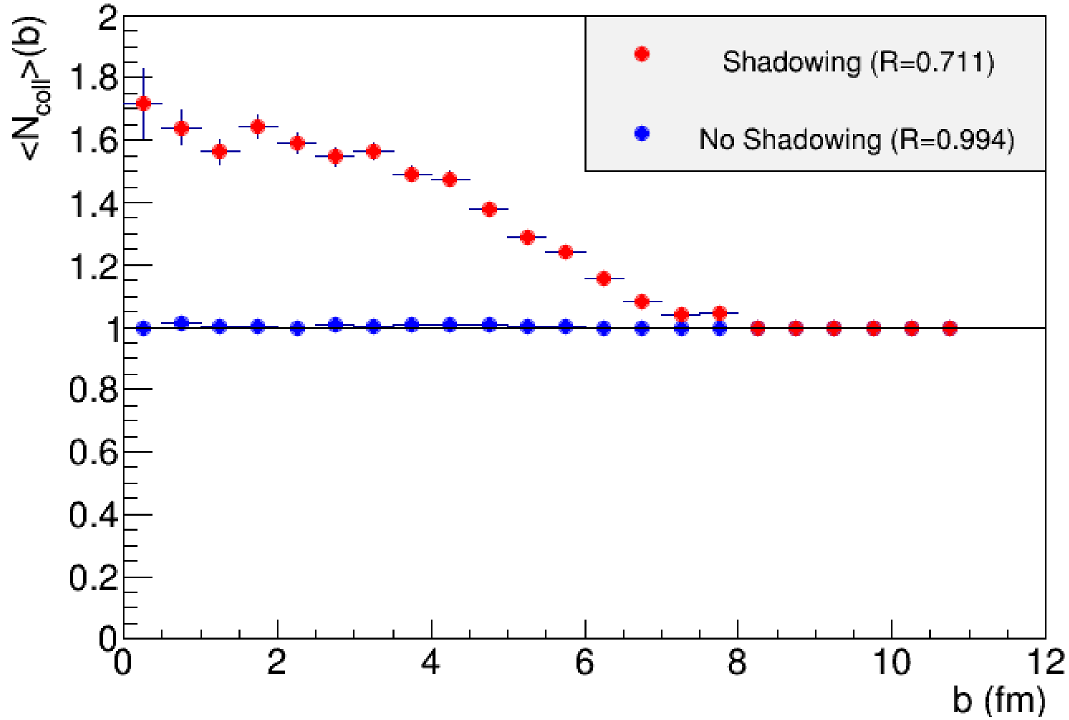




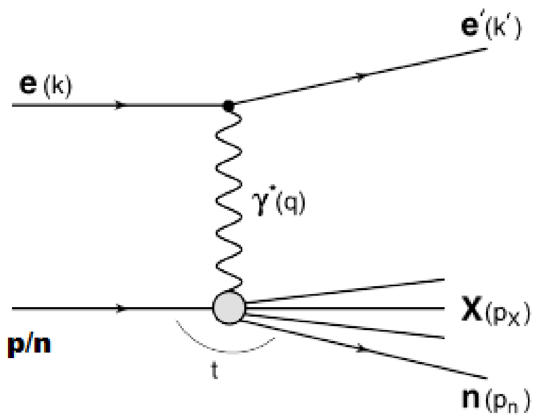
$N_{coll}(b)$ for $Q^2=1.69$ GeV^2, $x<<1$

$\sigma^A/\sigma^N(x,Q^2)$ ⟷ $\sigma_{dipole}(x,Q^2)$ ⟷ $P(N_{coll},b)$

- **Big difference between b=0 & b= R_{Au}=6.38 fm at low x,Q^2**
- **Geometry tagging easier. Now b is <u>directly</u> correlated with measurable activity**
- **Enhanced shadowing (& saturation?) at b=0 (recall $R=1/N_{coll}$).**

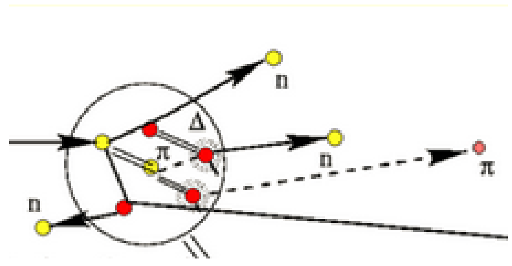


Event generation flow



Primary interaction

+



Intranuclear cascade

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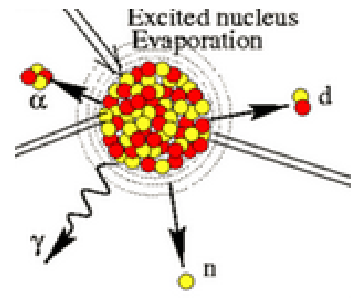


Nuclear remnant evaporation

Hard interaction on one nucleon:

e+p/n -> X

All ep/en underlying processes are possible.

Secondary interactions with the rest of the nucleon before flying outside

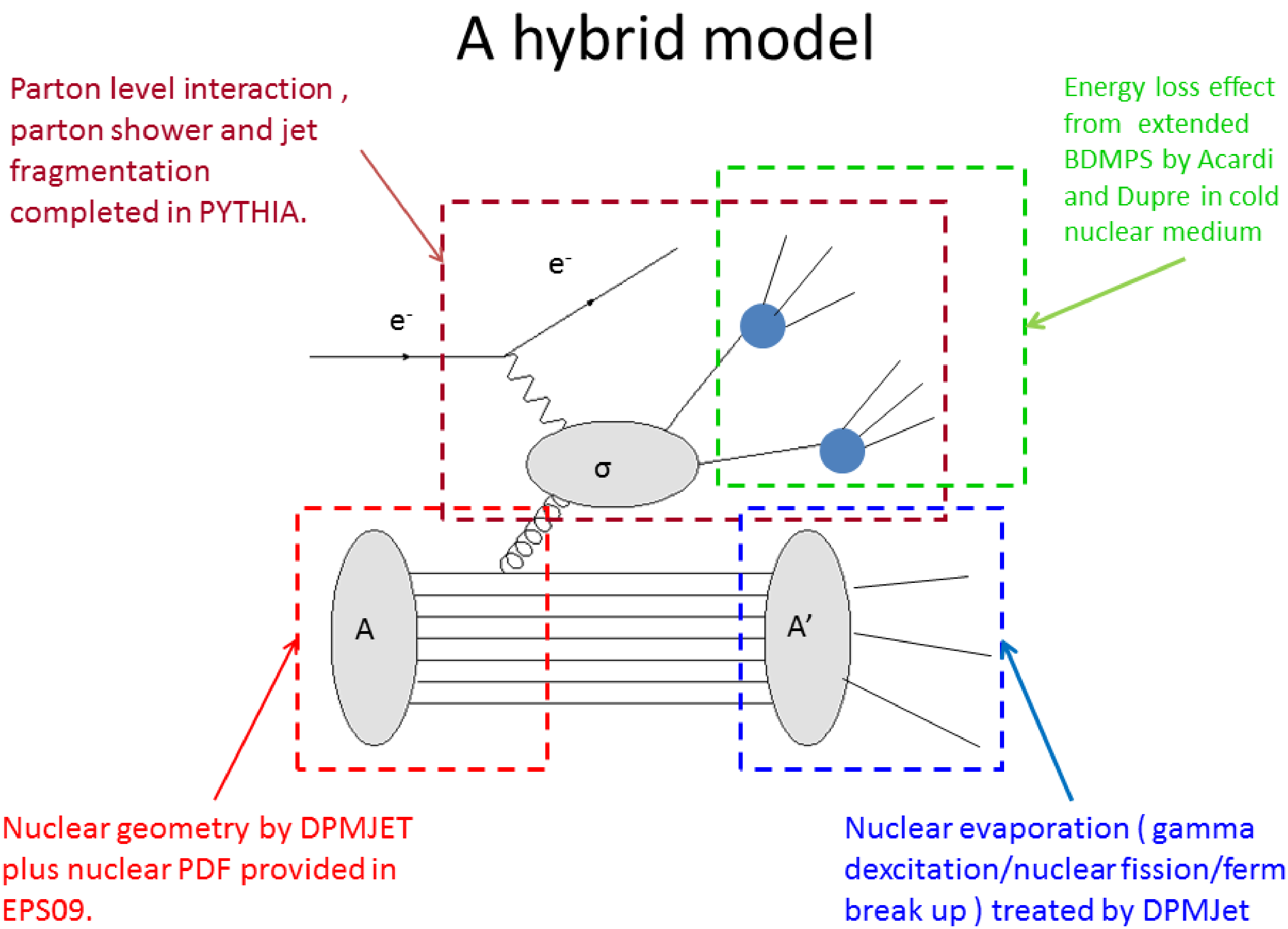
$h + N \to h^{(*)} + N^{(*)}$

h = pi/K/p/n, N=p/n

Need only mass, charge, excitation energy, no memory for prior history

$$P_j(E)dE = \frac{(2S_j+1)m_j}{\pi^2\hbar^3}\sigma_{\rm inv}\frac{\rho_f(U_f)}{\rho_i(U_i)}EdE$$

Program structure



Physics of gluon saturation

"U.S.-Based Electron Ion Collider Science Assessment Committee"

Irvine, April 19, 2017

Jean-Paul Blaizot, IPhT-Saclay

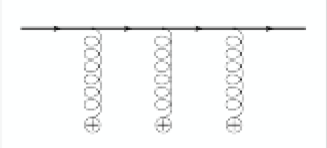
From J-P. Blaizot

Propagation of a fast parton in matter

$x^+ = \frac{t+z}{\sqrt{2}}$

Eikonal approximation

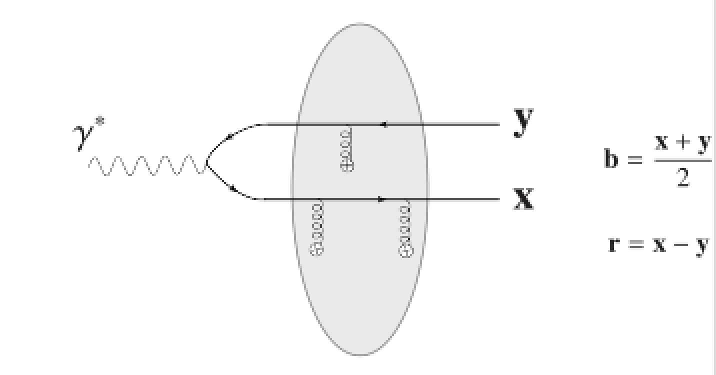
$$U(x) \equiv \mathrm{T}\exp\left(ig\int_{-\infty}^{x^+} dz^+ A_a^-(z^+, \boldsymbol{x}) t^a\right)$$



DIS in 'dipole frame'

$$\sigma_{\gamma^* p}(x, Q^2) = \int_0^1 dz \int_{\boldsymbol{r}} \left|\psi(Q^2, z, \boldsymbol{r})\right|^2 \sigma_{\mathrm{dip}}(\boldsymbol{r})$$

$$\sigma_{\mathrm{dip}}(\boldsymbol{r}) = 2\int \mathrm{d}^2\boldsymbol{b}\,(1 - \mathrm{Re}\,S(\boldsymbol{b}, \boldsymbol{r}))$$



Dipole nucleon/nucleus S-matrix

$$S(\boldsymbol{b}, \boldsymbol{r}) \equiv \frac{1}{N_c}\langle \mathrm{tr}\,(U_{\boldsymbol{x}} U_{\boldsymbol{y}}^\dagger)\rangle$$

Average over the field fluctuations of the target

From J-P. Blaizot

Saturation as a result of multiple scattering

Dipole-nucleon, at leading order (2 gluon exchange)

$$\sigma_{\rm dip}(r_\perp) = \frac{\pi^2\alpha}{N_c} r_\perp^2 x G_N(x, Q^2) \qquad (Q^2 = 1/r^2)$$

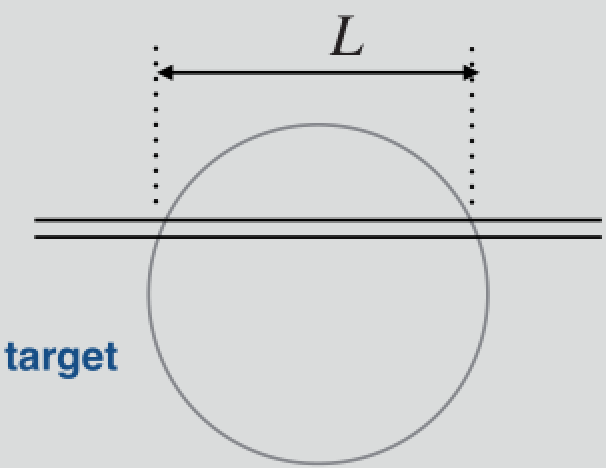
Color transparency for "small" dipoles

Dipole-nucleus, multiple scattering

Survival probability $S^2(\boldsymbol{b}, \boldsymbol{r}) = {\rm e}^{-L/\lambda}$ $\qquad \frac{1}{\lambda(r_\perp)} = \rho\, \sigma_{\rm dip}(r_\perp)$

$$S(b, r_\perp) = {\rm e}^{-Q_s^2 r_\perp^2/4}$$

$$Q_s^2 = \frac{2\pi^2\alpha}{N_c} \frac{A x G_N(x, 1/r_\perp^2)}{\pi R^2}$$



"small" or "large" depends on the gluon density of the target

"small" $(r_\perp Q_s \ll 1)$ **color transparency**

"large" $(r_\perp Q_s \gg 1)$ **black disk limit**